November 30th 2004

UC Berkeley's Demand Response (DR) Enabling Technology Development (ETD) Project

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In collaboration with the multidisciplinary team of:

Edward Arens & Charlie Huizenga (Buildings),
David Auslander (Controls), David Culler (O/S),
Jan Rabaey (Radios), Richard White (Sensors)

& students (many thanks to them!) at UC Berkeley

Multidisciplinary Team

Low Power Radios

Mesh Networking

Energy Scavenging

Sensors

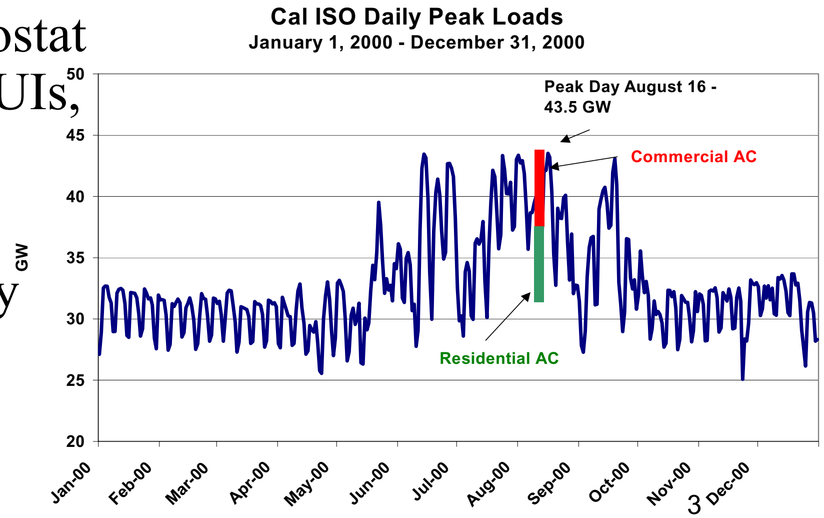
Buildings

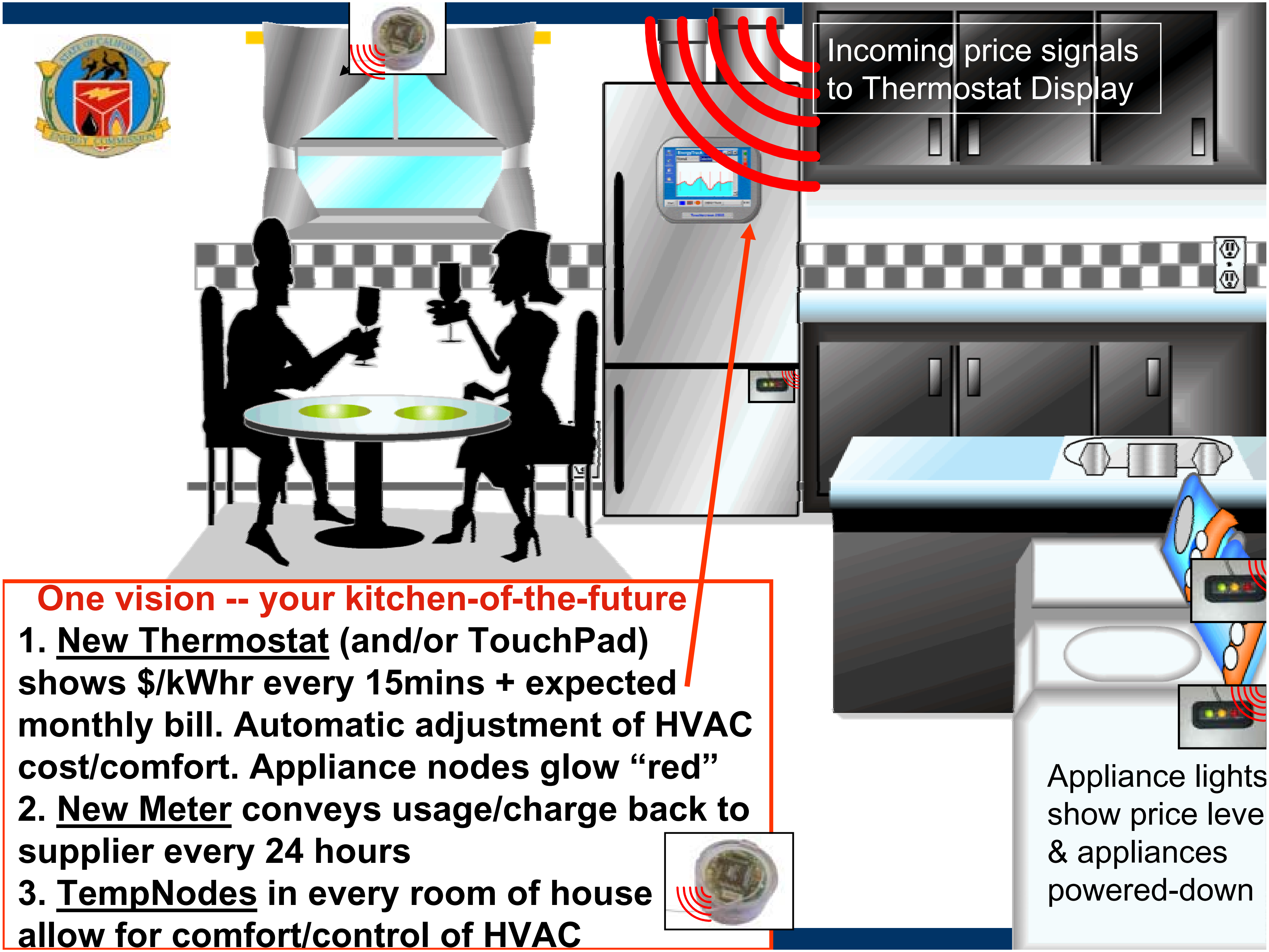
Controls

Manufacturing

Prototypes not Products !

- **Goals include: Reduce blackouts at peak usage times**
- **Enabling Technology Development: Key to research approach**
  - Meters, thermostats, temperature-nodes: In ad hoc self organizing wireless networks (low power radios, energy scavenging, TinyOS)
  - “Cheaper better faster” for the 10x10x10 mission of DR-ETD program
  - Residential focus in CA and affordable for even the smallest homes
- **One working scenario/vision to demonstrate new technologies**
  - Receives price signals every 15 mins (emergency signals treated immediately)
  - Users provide preferences to their thermostat and major appliances, thru easy to use GUIs, acting as the users proxy
  - Eventually -- self-learning systems
  - Time stamped usage sent back once a day -- say at 3am -- Or in an emergency the response would be immediate





One vision -- your kitchen-of-the-future

1. <u>New Thermostat</u> (and/or TouchPad) shows $/kWhr every 15mins + expected monthly bill. Automatic adjustment of HVAC cost/comfort. Appliance nodes glow "red"
2. <u>New Meter</u> conveys usage/charge back to supplier every 24 hours
3. <u>TempNodes</u> in every room of house allow for comfort/control of HVAC

Vision: Integrate these four Enabling Technologies for a 10x10x10 mission

- **1. Controls & applications on a prototype of New Thermostat**
  - Easy-to-use “thermostat” that can act as an automatic proxy to optimize energy savings versus comfort under varying energy price conditions.
- **2. Voltage/Current Sensors and relation to New Meter**
  - Low-cost wireless, passive and non-intrusive current and voltage sensing for application to the next generation meter and other devices.
- **3. Pico Radio & TinyOS for networking of devices**
  - Low-power and low-cost radio platforms, supported by appropriate operating systems, for ad hoc sensor and actuator network applications.
- **4. Energy Scavenging (important for Temp Nodes)**
  - Infinite life power source that scavenges energy from the environment. Possible energy sources include solar, vibration, air flow, and hybrid.

Topic 1: Controls/Thermostat

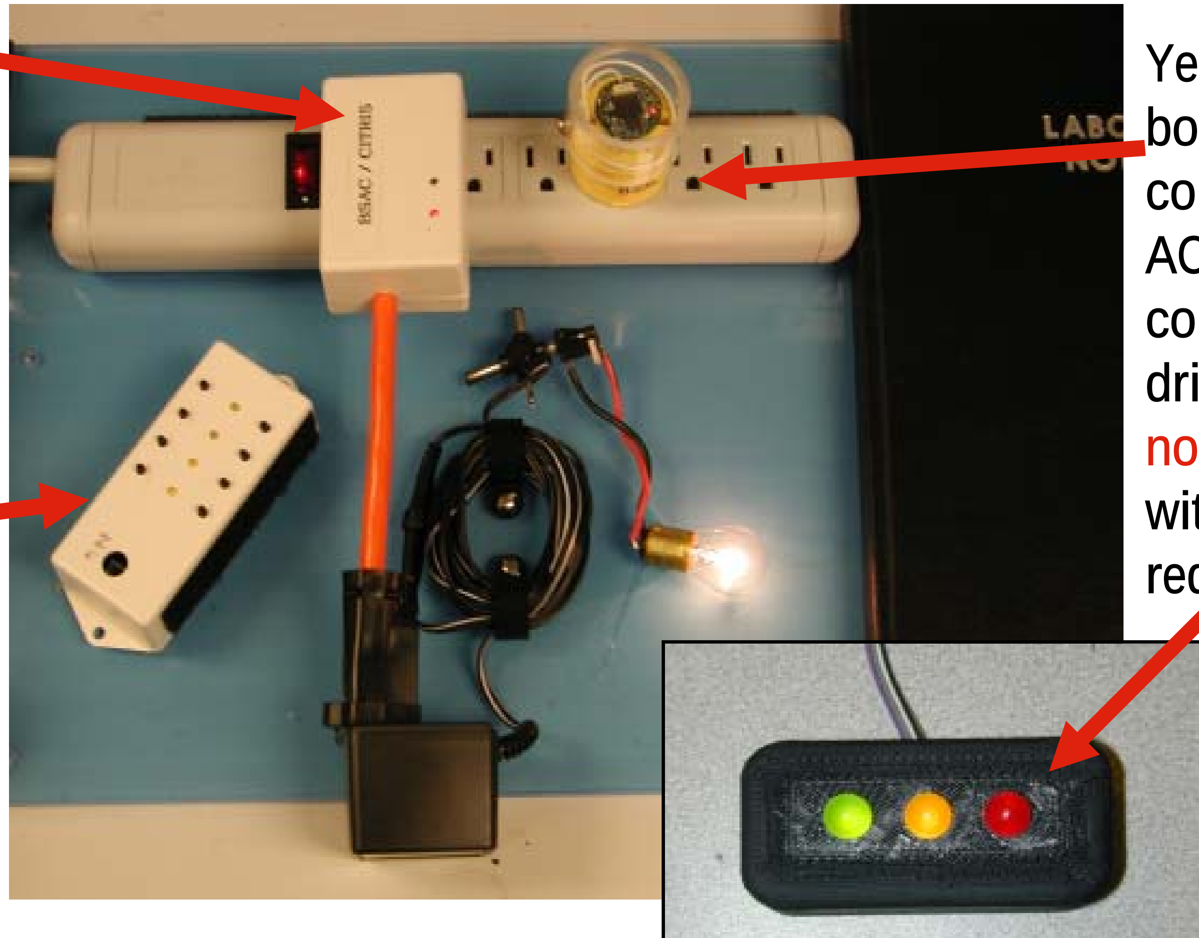
Challenges:

- Interface that's easy to understand and intuitive -- for many sectors of society.
- Learning algorithms that will optimize energy savings and comfort with time-varying energy prices (e.g. pre-cooling algorithms)
- Display to the user the expected monthly bill ("shock effect of monthly credit-card-bill")
- Control strategies for a house that can react to the possibility of low in-house network quality or complete network failure.

Wireless Controlled Outlets

Wireless node inside the box controls latching relay, turning lamp at right on or off.

Or, "Remote control" can communicate with node.



Yellow plug body contains AC/DC converter driving node shown with lighted red LED.

Appliance "Traffic Light"

Demo in
Full-scale Testbed

Topic 2: Sensor Measurements applicable to New Meter & other devices

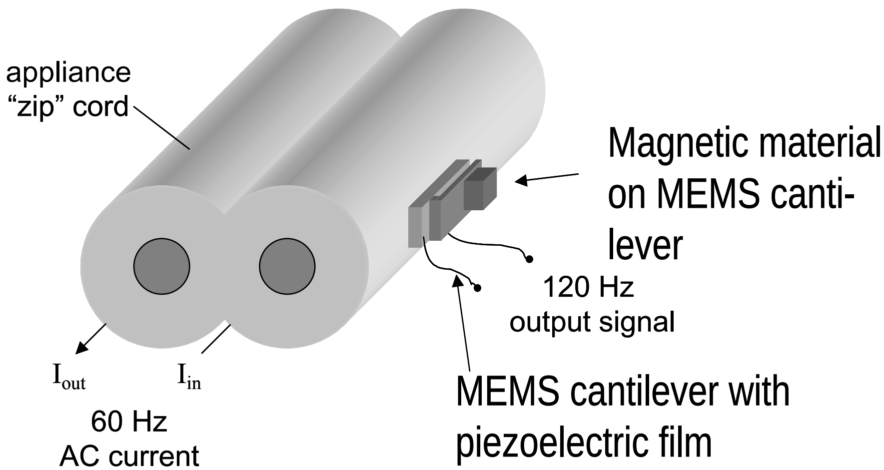
Needs

- **AC current sensing (see next slide)**
- **AC voltage sensing**

Specifications

- **Wireless data transmission of home-usage**
- **No external power source required**
- **Proximity coupling for inexpensive installation**

MEMS current sensor (prototype)



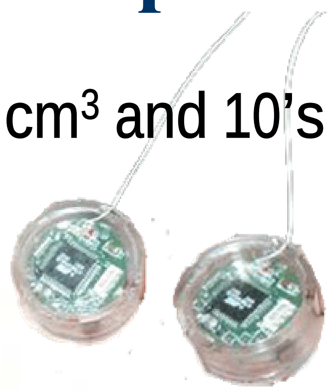
AC current sets up time-varying magnetic field whose gradient exerts force on high-permeability magnetic material at end of MEMS cantilever resonator, which vibrates and generates piezoelectric output voltage

<u>Electric current (magnetic field) measurement techniques</u>:

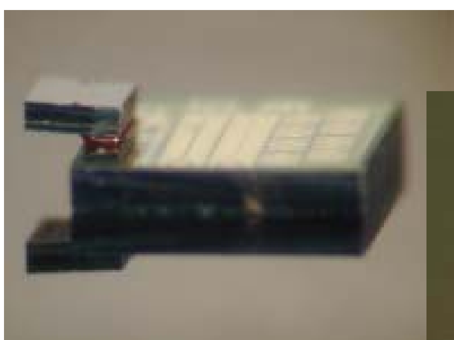
- Inductor
- Hall effect
- GMR sensor
- Magnetic force on MEMS sensor

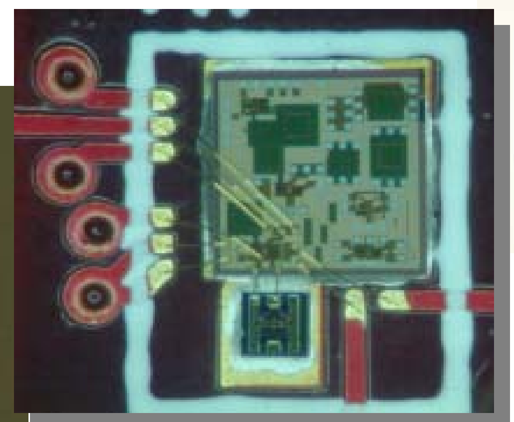
Topic 3: Radios and TinyOS

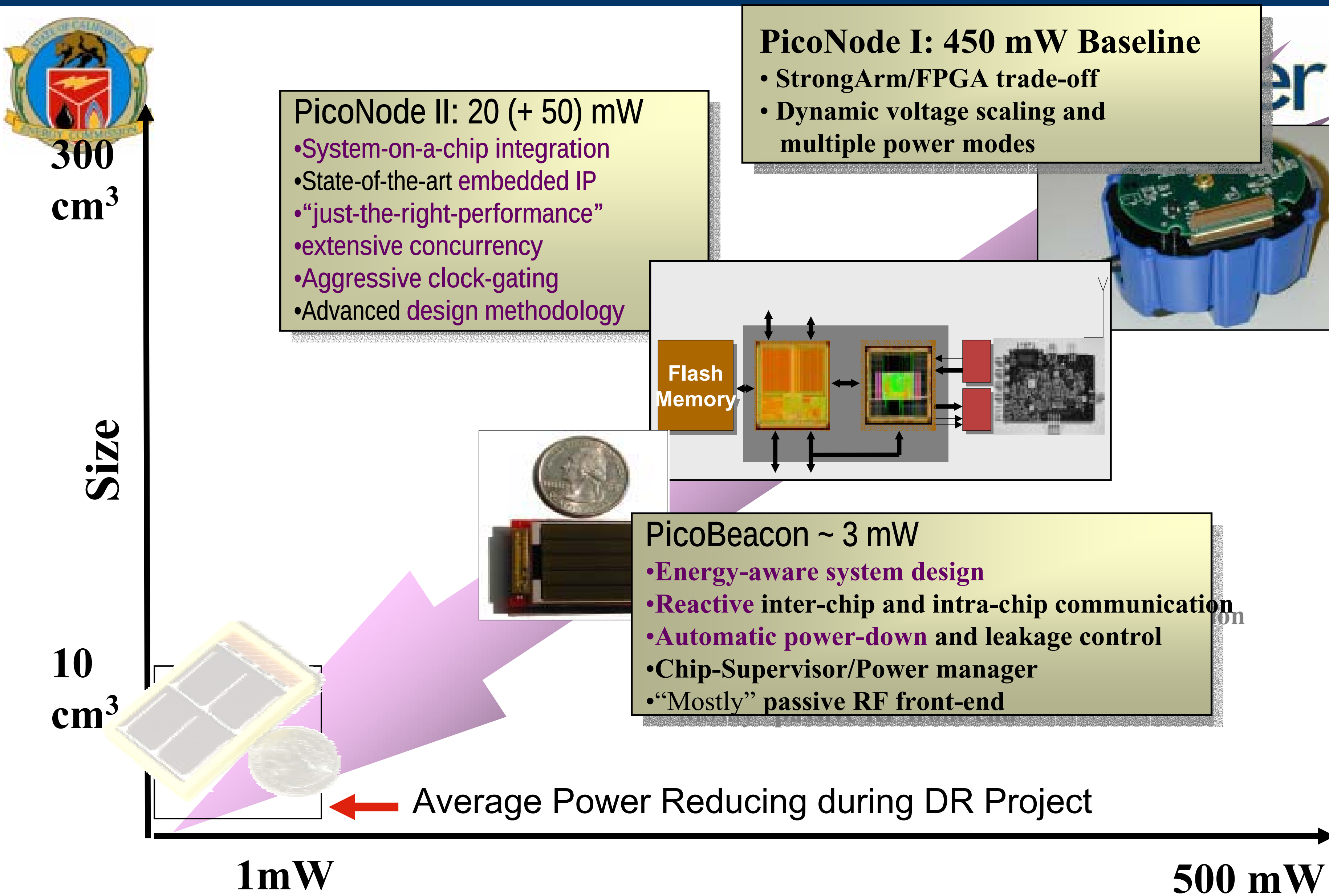
From 10’s of cm^3 and 10’s to 100’s of mW



To 10’s of mm^3 & 10’s of μW

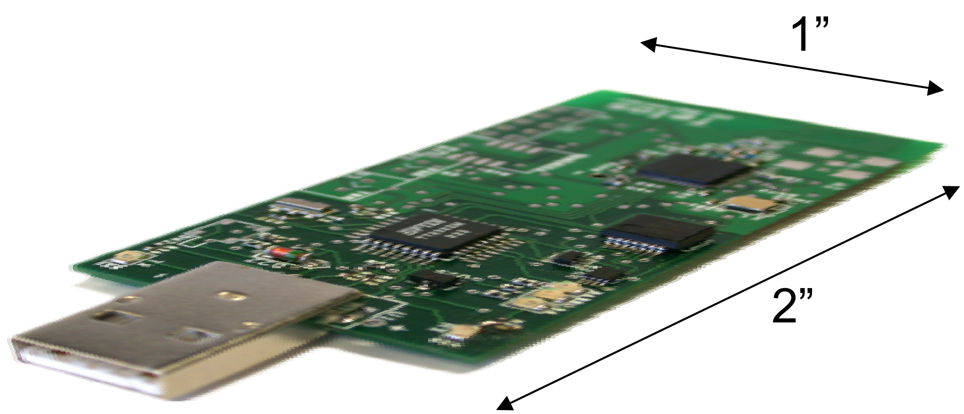





PicoNode I: 450 mW Baseline
• StrongArm/FPGA trade-off
• Dynamic voltage scaling and multiple power modes
PicoNode II: 20 (+ 50) mW
•System-on-a-chip integration
•State-of-the-art embedded IP
•“just-the-right-performance”
•extensive concurrency
•Aggressive clock-gating
•Advanced design methodology
Flash Memory
PicoBeacon ~ 3 mW
•Energy-aware system design
•Reactive inter-chip and intra-chip communication
•Automatic power-down and leakage control
•Chip-Supervisor/Power manager
•“Mostly” passive RF front-end
300 cm³
Size
10 cm³
Average Power Reducing during DR Project
1mW
500 mW

TinyOS on Nodes (called ‘Motes’)

CPU	
Bus Speed	8 MHz
RAM	2 Kb
Program Space	60 Kb
External Flash	512 Kb
Serial Communications	DIO,SPI,I2C,UART
Current (active w/ radio on)	19 mA
Current (sleep)	2.4 μA
Voltage	2.0-3.6V
Radio	
Frequency	2400-2483 MHz
Data rate	250 kbps
Output Power	-25 to 0 dBm
Antenna	Microstrip Inverted-F
Humidity Sensor	
Humidity Accuracy	3.5% RH
Temperature Accuracy	0.5 °C
Electromechanical	
Battery	2xAA, 2/3A

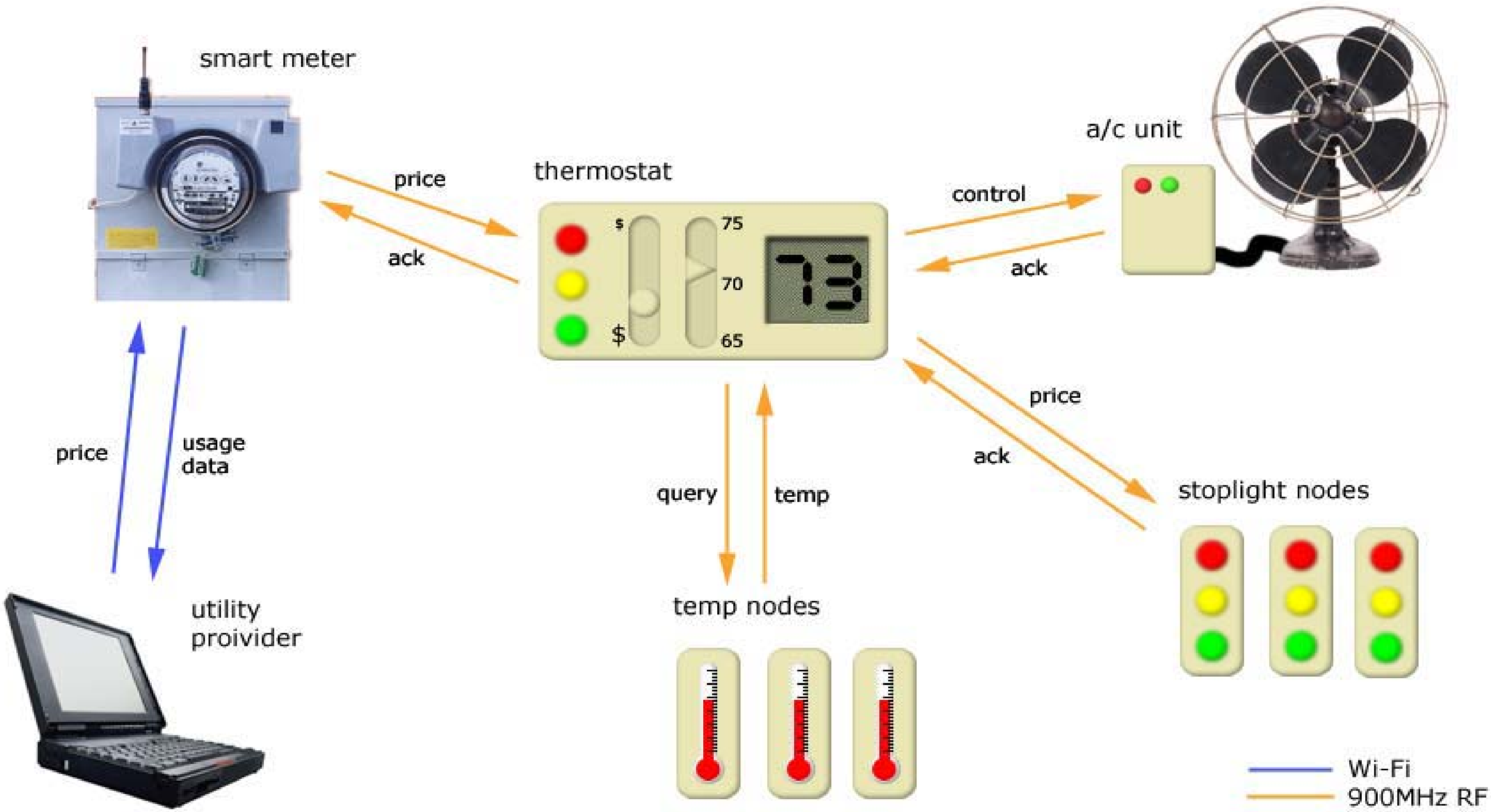


Ultra Low Power Node {called ‘Telos’}

16-bit microcontroller has a sub 1mA sleep state and can rapidly wakeup from sleep in under 6ms.

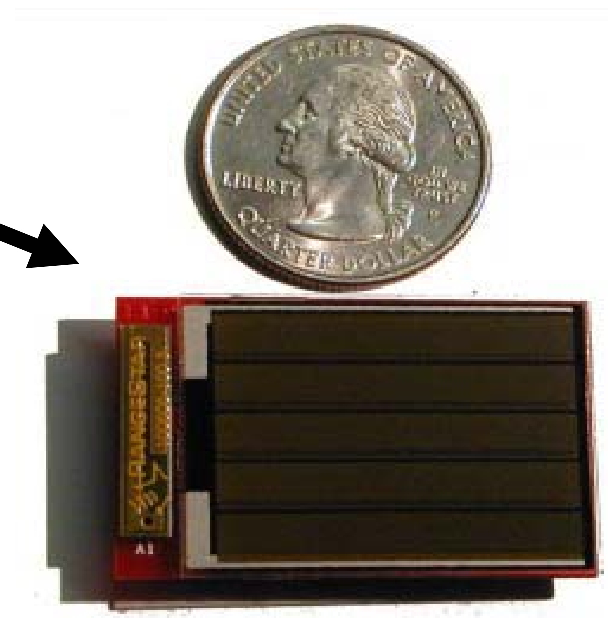
Telos operates down to 1.8V to extract as much energy as possible from the battery source.

TinyOS supports mesh-networked devices Testbed topology (not limiting!)



Topic 4: Energy Scavenging* Possibilities: "No replaceable batteries" on nodes

- Solar/Ambient Light
- Vibrations
- Air Flow
- Temperature Gradients
- Pressure Gradients
- Human Power



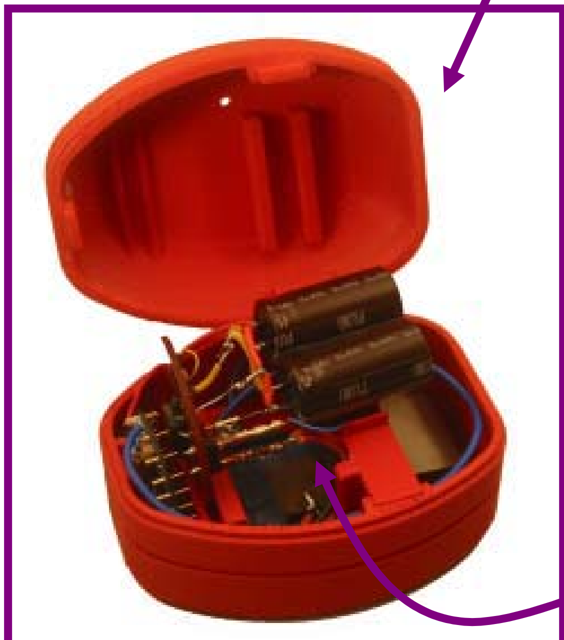
*water meter, gas meter

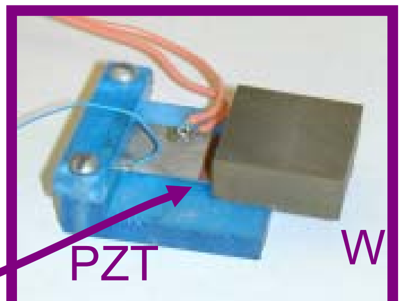
Vibration-Based-Scavenging:

Impact of ‘MicroPower’ on CA ‘GigaPower’ Challenges

Sources

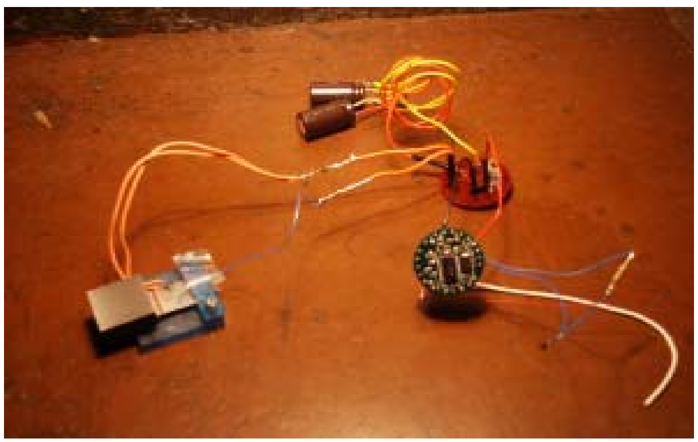
- HVAC ducts
- Raised Floors
- Motors
- Large windows
- Mount under wooden staircase





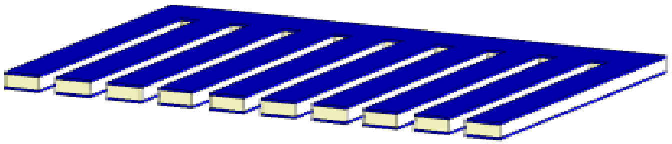
- **Three Rules for Design**
  - $P \sim M$
  - $P \sim A^2$
  - $P \sim 1/\omega$
- **PZT-shims with W-mass**
  - Early work ~ 800 $\mu W/cm^3$ at 5 m/s^2 (on a clothes dryer!)
- **Recent successes**
  - TinyTemp Node on stairs
  - MEMS piezo bender

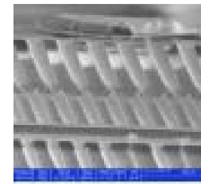
TinyTemp/TinyOS Node

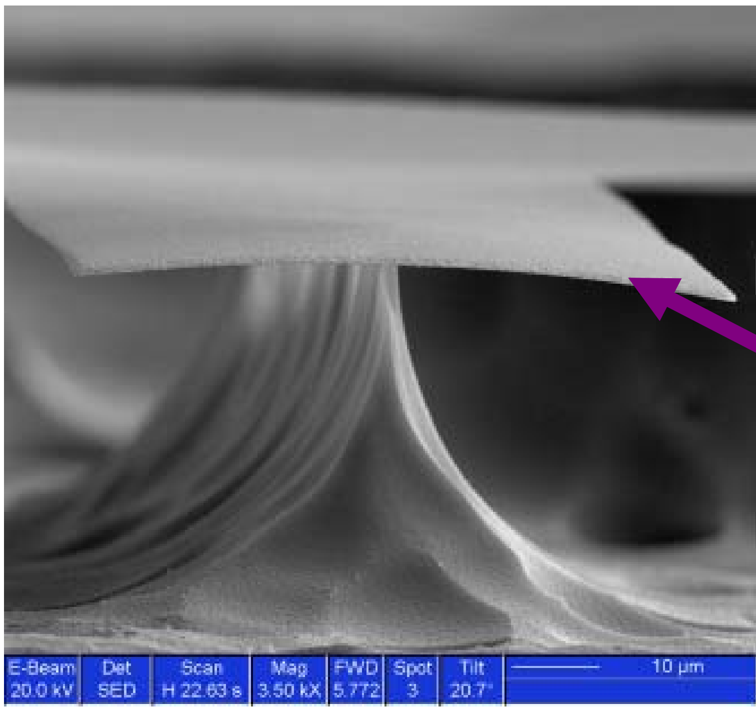


- Stair-Case Vibrations from Running Up and Down Stairs
- Piezoelectric: PZT
- Tungsten Alloy Mass: 52 g
- Beam Dimensions:
- 1.25” x 0.5” x 0.02”
- Resonant Frequency: 26.8 Hz
- Power Output: 450 µW

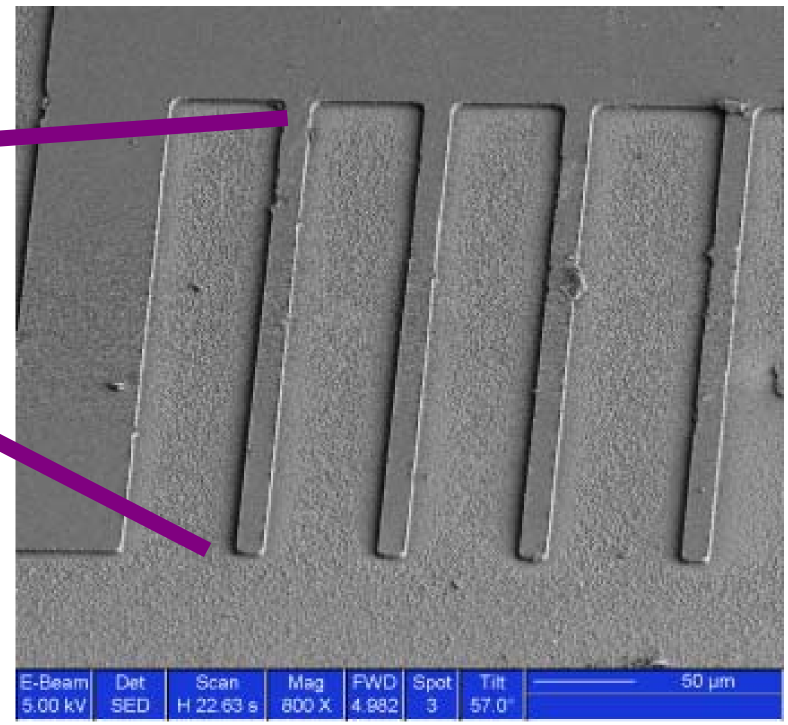
Schematic vs. Actual Device







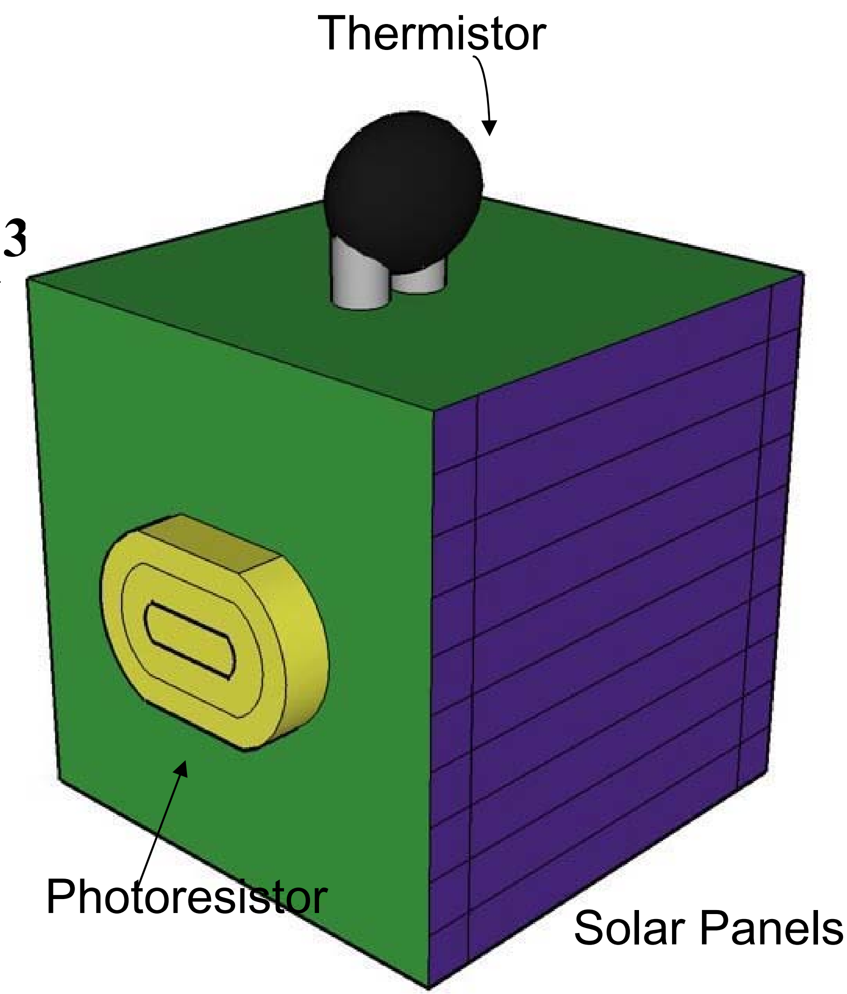
End-on view of one MEMS cantilever



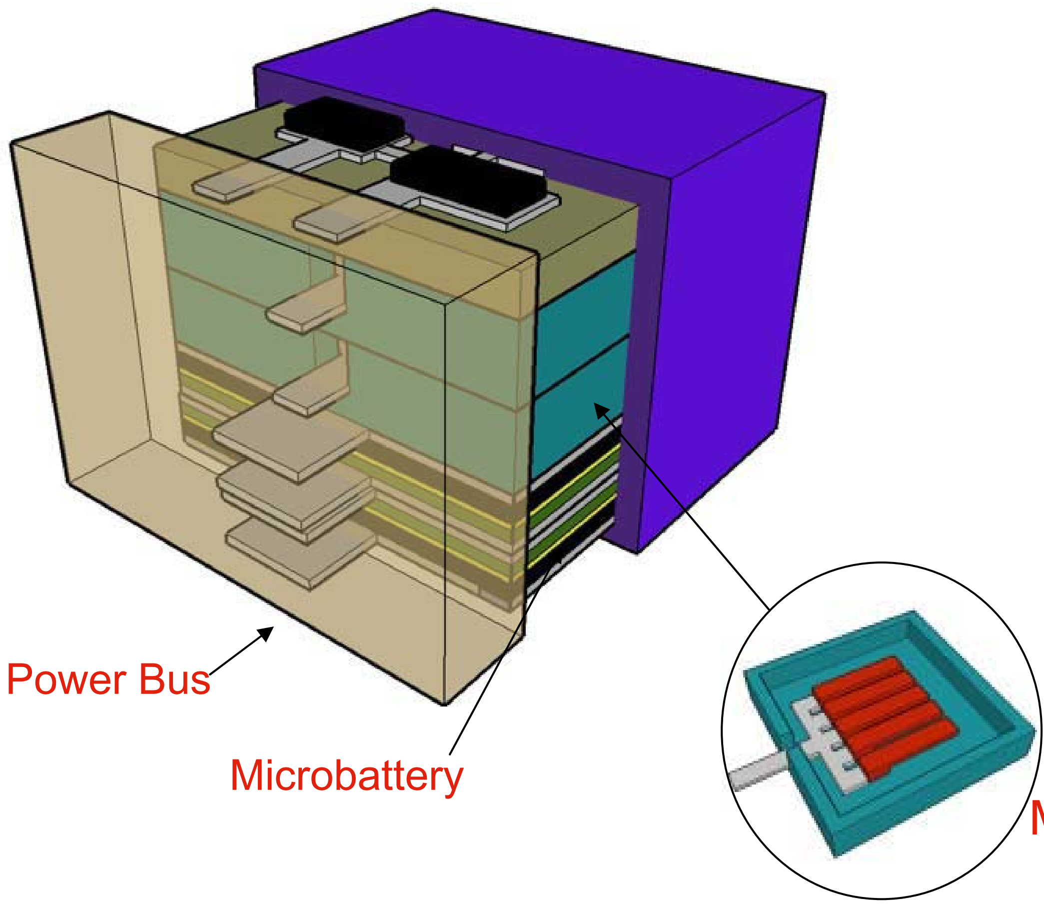
View from above of MEMS cantilevers…

Achieving 10x10x10

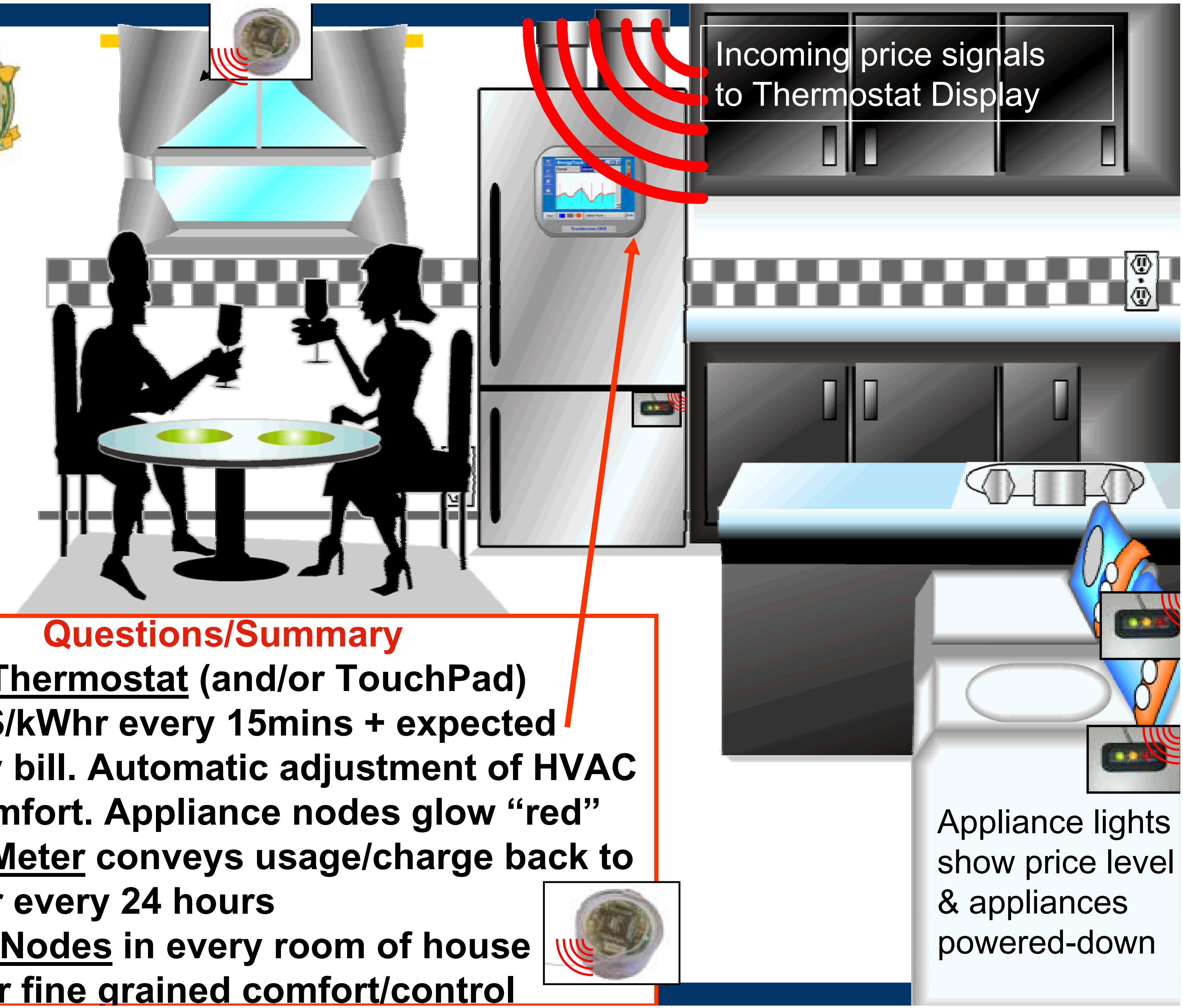
- **Early thinking about integrated device ~1 cm^3**
  - 3-D wiring
  - 4 sides with solar panels
  - 2 sides with sensors
  - On-board recharg. battery
  - On-board piezo electric generation



Achieving 10x10x10



- One package
- One bus
- Test bed for integration
- Wiring problem still avoided



Questions/Summary

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